1977

A three platform experiment on optical turbulence in the marine boundary layer.

Paine, Richard Henry

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A THREE PLATFORM EXPERIMENT ON OPTICAL

TURBULENCE IN THE MARINE BOUNDARY LAYER

by

Richard Henry Paine

March 1977

Thesis Advisor: K. L. Davidson

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) A Three Platform Experiment on Optical Turbulence in the Marine Boundary Layer	5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; March 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard Henry Paine	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940	12. REPORT DATE March 1977
	13. NUMBER OF PAGES 66
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, California 93940	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An observational experiment was conducted in the marine boundary layer off the California coast involving optical turbulence measurements. The measurements were made from a ship, a tethered kite and two C-135 aircraft. Measured values of C_n^2 from the surface to levels above the marine inversion were related to the synoptic weather situation. C_n^2 values were observed to be maximum in the

inversion. However, C_n^2 height distributions were quite complex with extrema occurring at several levels. Near surface C_n^2 values, measured from two levels on the ship, exhibited expected diurnal changes. Overall, C_n^2 values measured optically (scintillation) and meteorologically (from C_T^2 measurements) compared satisfactorily. C_n^2 profiles estimated from surface observed values using a $z^{-4/3}$ assumed distribution appeared to define the mean measured profile.

Approved for public release; distribution unlimited.

A Three Platform Experiment on Optical Turbulence in the Marine Boundary Layer

by

Richard Henry Paine
Captain, United States Air Force
B.S., University of Washington, 1970

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 1977

ABSTRACT

An observational experiment was conducted in the marine boundary layer off the California coast involving optical turbulence measurements. The measurements were made from a ship, a tethered kite and two C-135 aircraft. Measured values of C_n^2 from the surface to levels above the marine inversion were related to the synoptic weather situation. C_n^2 values were observed to be maximum in the inversion. However, C_n^2 height distributions were quite complex with extrema occurring at several levels. Near surface C_n^2 values, measured from two levels on the ship, exhibited expected diurnal changes. Overall, C_n^2 values measured optically (scintillation) and meteorologically (from C_T^2 measurements) compared satisfactorily. C_n^2 profiles estimated from surface observed values using a $z^{-4/3}$ assumed distribution appeared to define the mean measured profile.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Better understanding of electro-optical systems and the atmospheric environments in which they must operate has become increasingly important with recent increases in the use of such systems. This increased application is occurring in both the civilian and military communities. The civilian community has developed operational systems that usually avoid propagation through the atmosphere due to the many restrictions imposed by the atmosphere. The military has extended the use of electro-optical systems for transfer of energy, guidance of precision guided missiles, line-of-sight communications and for pointer trackers all of which necessitate propagation through the atmosphere. This study was conducted as a joint experiment by the Air Force and the Navy to expand the data base for evaluating electro-optical wave propagation in the marine environment as well as to gain further understanding of the mechanism of such propagation in the atmosphere.

The ambient atmosphere imposes limitations on optical propagation by atmospheric turbulence, absorption, and refraction. This experiment was an examination of the limitations imposed by atmospheric turbulence. Turbulence degrades the optical homogeneity of the atmosphere by causing small scale inhomogeneities in density which are random in size and distribution.

The scale of these turbulent related inhomogeneities varies from meters in the outer scale (Lo) to millimeters in the inner scale (lo) of turbulence. The various scales of interest appear in figure 1.

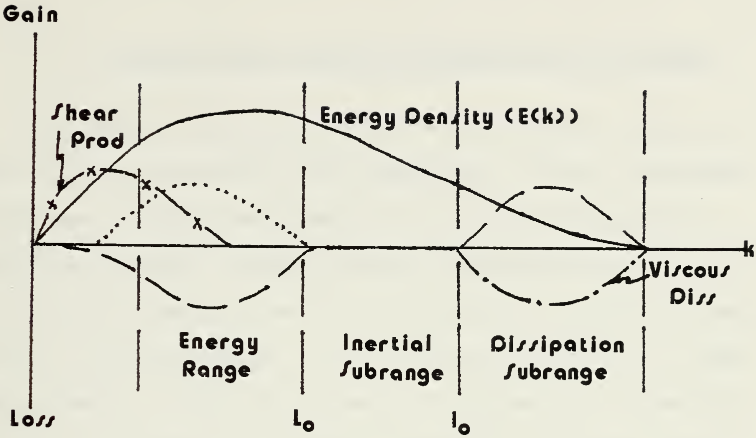


Figure 1. Energy Spectrum and Inertial Subrange.

At scale sizes greater than Lo, most of the turbulent kinetic energy is produced and at scales less than lo, the majority is dissipated into heat. The scales between Lo and lo comprise the inertial subrange of turbulence wherein turbulence is assumed to be isotropic and homogeneous. Turbulence with scale sizes from meters to millimeters is particularly disruptive to optical and millimeter wavelength propagations. The degradation effects of turbulence on electro-optical propagation are measureable by both micrometeorological and optical methods.

II. RELATION BETWEEN OPTICAL AND METEOROLOGICAL PARAMETERS

Of the three platforms used for measuring atmospheric effects on electro-optical propagation in this experiment, two were instrumented for micrometeorological measurements and one was instrumented for optical measurements. Micrometeorological measurement of optical turbulence involves measuring small scale temperature fluctuations, taking the mean of the fluctuations, and then relating the means to a turbulence parameter. Optical measurements of turbulence are accomplished by observing the means of intensity fluctuations of coherent light or by the interference patterns of coherent light over some distance in the atmosphere. The former optical measurement is referred to as scintillation and in this experiment the latter is referred to in terms of the Modulation Transfer Function (MTF) which is the ratio of image to object modulation for sinusoids of varying spatial frequency. There is a single parameter which can be used to relate meteorological and optical measurements. This parameter is the refractive index structure function parameter, C_n^2. C_n^2 is the only parameter necessary to describe the intensity of refractive index fluctuations over scales which contribute to spatial and temporal degradation of light coherence due to phase and amplitude distortion in propagating wavefronts.

The temperature structure function parameter C_T^2 was used to relate C_n^2 to micrometeorological measurements in this experiment. C_T^2 is the primary parameter in defining C_n^2 by:

$$C_n^2 = (79X10^{-6}\ P/T^2)^2\ C_T^2 \qquad (1)$$

Recent studies (Friehe, 1975) have shown that the humidity turbulence parameter may be a contributor to C_n^2 under certain conditions. However, this contribution was not considered in this experiment.

C_T^2 is defined as

$$C_T^2 = \overline{(T'(x)-T'(x+r))^2}/r^{2/3} \qquad (2)$$

where r is the distance between paired temperature probes and is greater than the inner scale lo, but less than the outer scale Lo.

Scintillation (optical) measurements can be related to C_n^2 on the basis of propagation theory which indicates that the logarithm of the intensity fluctuations has a normal distribution about its mean. The variance of this distribution (σ^2) is directly related to C_n^2 by

$$\sigma^2 = \text{constant X } k^{7/6} z^{11/6} C_n^2 \qquad (3)$$

where k is wave number, z is path length.

Quantitative reduction of MTF curves to C_n^2 was not possible in this experiment due to the form of the results made available for this thesis. A relationship between MTF curves and C_n^2 does exist, however, and it will be used to draw some general conclusions. The general relationship is that C_n^2 is a maximum, indicating strong shear interfering with optical propagation when the MTF curves have the greatest slopes.

III. HEIGHT VARIATIONS OF C_n^2

A significant aspect of the observations was the examination of vertical variations of C_n^2. Previous investigations have been made for this purpose. As early as 1966 captive balloons were used to measure C_T^2 above 200 meters (Koprov and Tsvang, 1966; Hufnagel, 1966: Volkov et al, 1968). In 1969, aircraft C_T^2 measurements were performed by Tsvang who observed a $z^{-4/3}$ height dependence of C_T^2 up to 500 meters in an unstable regime.

In the United States, the Air Force was interested in the high altitude implications of optical turbulence, the Navy was interested in low altitudes over the sea and the National Oceanic and Atmospheric Administration (NOAA) was interested in atmospheric propagation from a research standpoint through the Environmental Research Laboratories (ERL). In 1972, vertical distribution of C_n^2 was examined by the United States Air Force using the Airborne Laser Laboratory (ALL) (Morris, 1972). Four data gathering flights occurred between 1 and 15 January 1972, in which two NC-135 aircraft flew side by side over land. One aircraft was a transmitter aircraft and the other was the receiver. Two lasers, a He-Ne and a CO_2, were mounted in the transmitting aircraft and were directed at receivers and recorders in the other aircraft. The aircraft separation distances were varied at each altitude. The separation distances were .5, 1.0, 1.5, 2.0, 310 kilometers at each altitude and the altitudes were varied from 1.5 to 10.5 km above sea level in 1.5 km increments. Three of the four flights were from Kirtland AFB, New Mexico

to Wisconsin and return and the other was from New Mexico to Alabama and return. Neither route had major mountains nor major weather systems during the flights. Observed C_n^2 values were several orders of magnitude higher than had been expected. The aircraft boundary layer turbulence was first suspected as the reason for observed high C_n^2 values, but this suspicion was discounted so existing high altitude models were readjusted to these findings.

Another major effort to define C_n^2 height variations was that by NOAA's ERL using the ERL 150 meter tower in eastern Colorado and aircraft measurements over eastern Colorado and off San Diego (Lawrence and Ochs, 1972). On the tower, C_T^2 was measured from a sensor which traversed the vertical extent of the tower. Aircraft C_T^2 measurements were obtained from a level as close as possible to the surface up to three kilometers above the surface. In each case, C_n^2 maxima were observed at or near inversion levels. Furthermore, just below the inversion tops C_n^2 was observed to be about twice as large over water as over land and just above the inversion tops C_n^2 values were twice as large over land as over water. Large and frequent variations of C_n^2 were also observed in these experiments and hence, reasonable statistics could not be obtained from these results to describe mean occurrence of atmospheric turbulence. It was concluded that the development of effective remote sensing techniques were necessary to obtain such statistics.

Frish and Ochs (1975) evaluated vertical variations of C_T^2 obtained in the ERL experiment to derive an empirical expression for its height distribution. These data did not agree with Tsvang's (1969) $z^{-4/3}$ distribution nor with surface layer empirical results of Wyngaard et al (1971). Frish and Ochs observed that the ratio of the height in the

atmosphere to the height of the marine inversion was also a necessary parameter to satisfactorily describe the C_T^2 distributions.

In this particular experiment the interest was in both surface layer turbulence and its vertical distribution. There have been considerable efforts to establish turbulence relationships for the constant flux layer overwater. Paulson et al (1972) performed parallel experiments overwater to those done overland by Businger et al (1971). Investigations were begun at the Naval Postgraduate School in 1974 on the turbulence in the marine boundary layer in conjunction with electro-optical experiments. The turbulence experiments were based on shipboard measurements. At approximately the same time experiments were being conducted by the Air Force at Kirtland AFB, New Mexico in support of laser research. This experiment involved a balloon-borne instrument called a thermosonde that measures and transmits in situ C_T^2 values. In 1975 the Air Force decided to rejuvenate the Airborne Laser Laboratory experiment for measuring C_n^2 at different altitudes with a specific interest in high altitudes. These experiments were to use the same C-135 aircraft used in Morris's experiments of 1972 but the missions were to be more sophisticated, longer, and also include terrain considerations. With the rejuvenation of this experiment a joint Navy and Air Force experiment was proposed using three platforms for measuring C_T^2 or C_n^2. The ship and micrometeorological instrumentation aboard the ship (C_T^2) was one platform, the kite-borne thermosonde (C_T^2) was a second platform and the two C-135s (C_n^2) were the third platform. The platforms will be described in more detail in the Experimental Procedure section of this thesis.

The objectives of the joint Navy-Air Force experiment were to:

1. Extend the data base to the Navy's operating environment
2. Determine the dependence of C_n^2 from the surface through the marine inversion layer
3. Model the C_n^2 dependence as a function of easily measureable meteorological parameters
4. Predict High Energy Laser (HEL) propagation in the lower marine atmosphere
5. Correlate optical and temperature based C_n^2
6. Establish a data base for modeling aerosol size distributions

IV. EXPERIMENTAL PROCEDURES

Important aspects of this experiment pertain to how the ship and the aircraft were situated relative to each other and how the small scale turbulence was measured. In this section the experiment and the instrumentation used are described in detail.

In this experiment there were three individual units. The ship was one unit, the two C-135 aircraft were a second unit, and the Navy S-2 Atmospheric Sampler aircraft was a third unit. The locations of each and their relative movements appear in Figure 2. The R/V Acania was stationed near 36°N 123°25'W during the experiment. It maintained this position to be near the centerpoints of the aircraft flight paths.

The C-135 aircraft were required to fly in formation as a unit by nature of being the endpoints of a propagation path. The C-135 passes began along a 60 mile northwest to southeast flight path with the centerpoint near the Acania and was followed by a second pass from southeast to northwest. The passes continued in this order until nine passes had been completed. The aircraft coaltitudes varied from 2.134 km at the entrance and exit of each pass to .15 km at the centerpoint of the pass near the Acania. The aircraft separation was maintained at one kilometer and the airspeeds never exceeded .41 mach.

The Navy S-2 was the third unit of the experiment. Its passes were parallel to and synchronous with the passes of the C-135s although the passes were only 36 miles long due to the slower airspeed. The S-2 was displaced two miles to the east of the C-135 flight path. The elevation

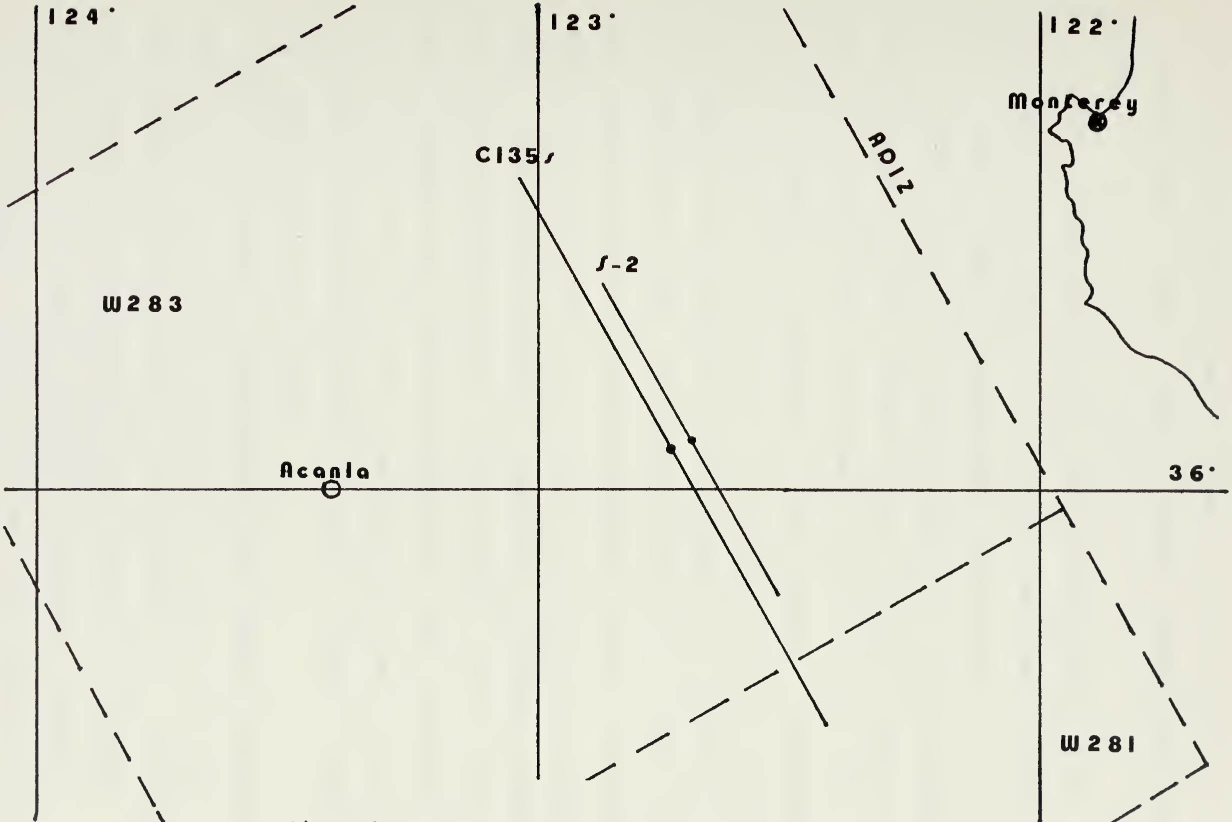


Figure 2. Platforms - Locations and Flight Paths.

varied from the top of the temperature inversion at the entrance and the exit of the pass down to .1 km at the middle of the pass near the Acania.

Devices for measuring C_T^2 and C_n^2 were mounted aboard the ship, on a captured kite, and on the C-135 aircraft. Measurement systems on each of these platforms will be described in detail below.

As part of the Navy's high energy laser program, overwater boundary layer turbulence has been investigated from the R/V Acania which has been equipped with profile and turbulence equipment to measure wind velocity, humidity, and temperature at several levels. C_T^2 temperature probes are mounted on towers positioned at and near the bow of the ship. The heights of the two probes in this experiment were 4.2 meters and 7.6 meters above sea level. The tower locations appear in Figure 4 and the mounting arrangement on the towers appears in Figure 3. Temperature fluctuations were measured using resistance wire bridges with platinum wires. The system has a response to temperature fluctuations as small as 0.004°C in magnitude and up to 1 kHz in frequency. The data were processed aboard ship to obtain ten minute means. This was performed with a microprocessor based data processing system called MIDAS (Microprocessing, Integrated Data Acquisition System). The mean C_T^2 values were later converted to C_n^2 values.

Optical turbulence was also measured by the thermosonde suspended over the ship. The suspended thermosonde was tethered to the Acania and winched up and down to obtain a vertical profile of C_T^2. Two systems were used during the experiment to provide lift for the thermosonde package. The first, a Kytoon, was used on 15 Sep and is pictured in Figure 5. The second, a Jalbert Airfoil, was a more capable lift mechanism and was used on 16 Sep. The airfoil is pictured in Figure 7.

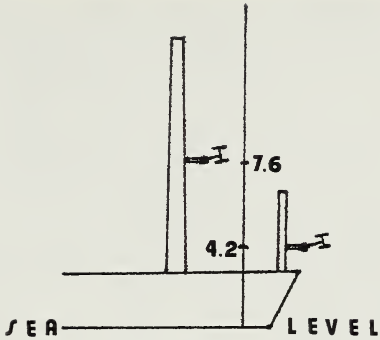


Figure 3. Sensor Location Aboard Ship.

The thermosonde unit provided in situ measurements of C_T^2. It was developed to support the laser research program at the Air Force Weapons Laboratory. The thermosonde appears in Figure 6 and is shown suspended from the airfoil in Figure 7. C_T^2 values are obtained from the temperature difference between two fast response fine wire probes. The thermosonde output is based on Equation (2). Analog data were telemetered to a receiver and recorded on both strip chart and on magnetic tape. The recorded data were processed to obtain 30 second running means of approximately five Root-Mean-Square sampling periods per mean and then C_n^2 was obtained from these C_T^2 values using Equation (1). For this conversion the pressure at the height of the thermosonde was obtained by the formula:

$$P = Po \exp(-h/26000) \qquad (4)$$

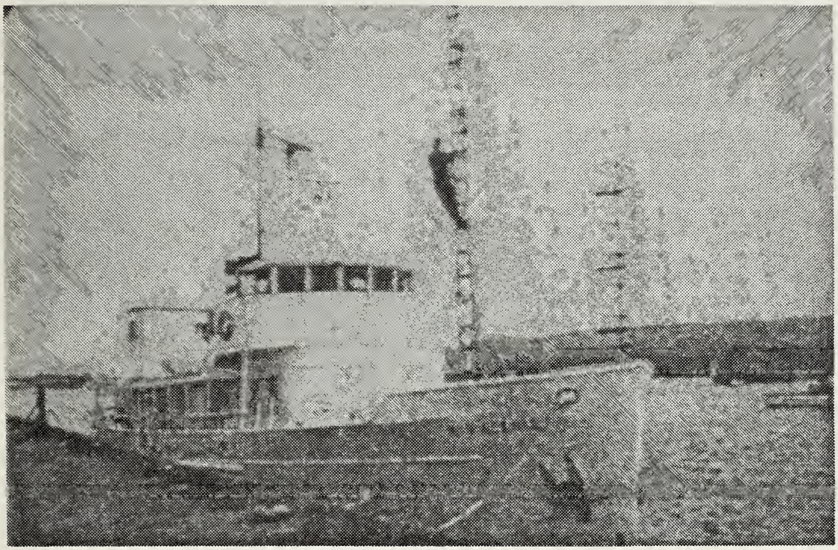


Figure 4. R/V Acania and Equipment Towers.

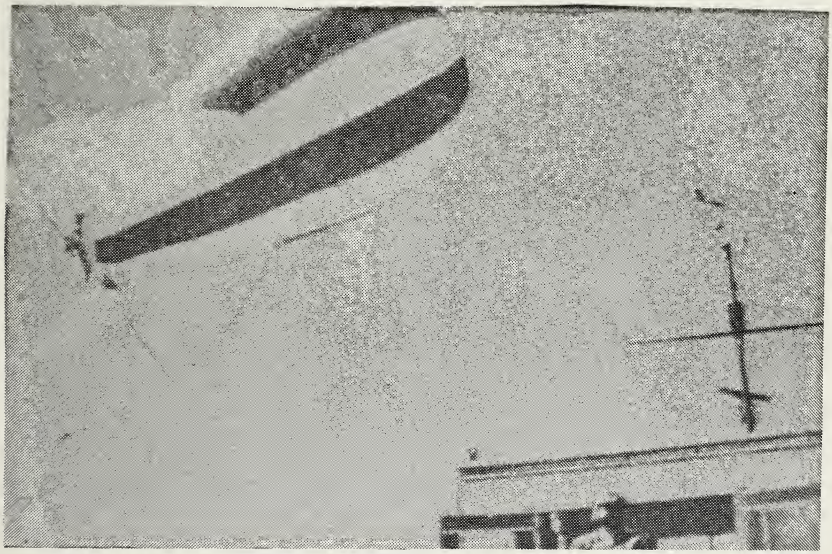


Figure 5. Kytoon.

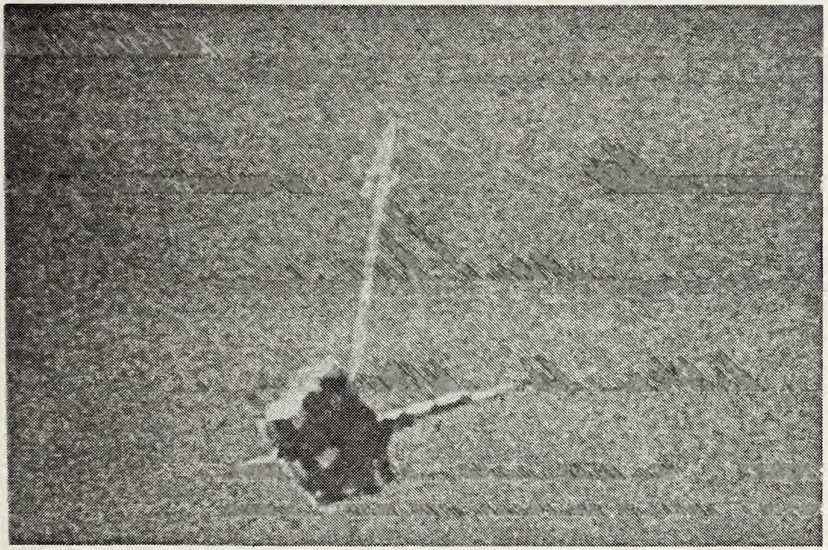


Figure 6. Thermosonde.

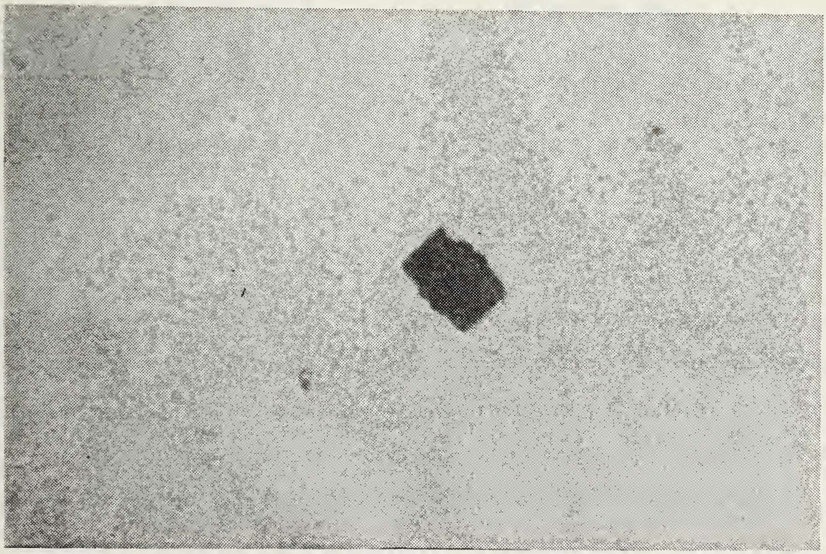


Figure 7. Thermosonde Suspended from the Jalbert Airfoil.

where Po is the surface pressure and h is the thermosonde elevation in feet. The thermosonde elevation was estimated on the basis of sextant readings and the length of tether line. The temperature was obtained from the average of the temperature profile as recorded by the S-2 Atmospheric Sampler.

The last device for measuring C_n^2 was aboard the C-135 aircraft. The aircraft configuration appears in Figure 8, pictures of the aircraft on the ground appear in Figures 9 and 10 and an inflight picture appears in Figure 11. The latter picture was obtained during the experiment.

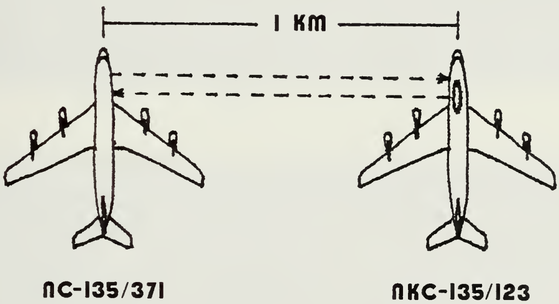


Figure 8. Aircraft Relative Positions.

C_n^2 was obtained from the C-135 by optical measurement. The experimental procedure was to shine laser beams from one aircraft to another keeping a very accurate fix on where the laser beams were pointing. In order to keep an accurate fix on the receivers, tracking benches were installed in each aircraft. These benches were controlled by a television and a sensitive electronic servo mechanism and were designed to keep the beam

Figure 9. NKC-135/123 on Ground.

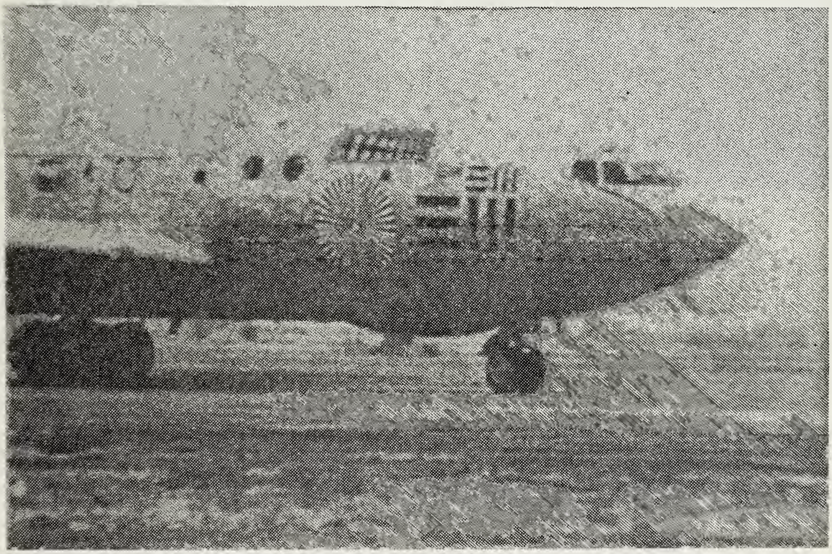


Figure 10. NC-135/371 on Ground.

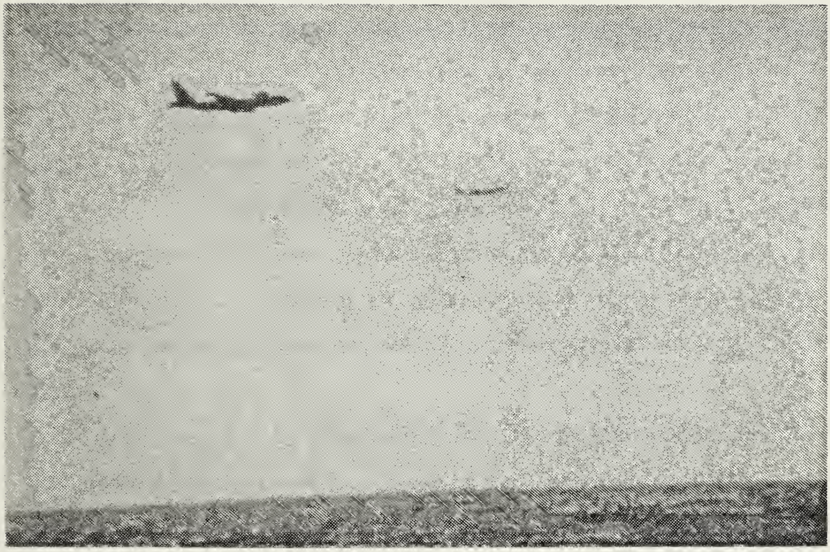


Figure 11. C-135 Aircraft in Flight.

within an accuracy of one milliradian. Referring to Figure 8, the forward laser was mounted in aircraft NC-135/371 and used as the data beam as well as to run the tracking bench in aircraft NKC-135/123. The aft laser beam was mounted in aircraft NKC-135/123 and used to run the tracking bench in aircraft NC-135/371. Specifications for the low power lasers are given in Appendix A.

The scintillometer aboard NKC-135/123 was designed to measure values of C_n^2 in this experiment. A scintillometer measured the turbulence induced fluctuations in coherent light intensity. These fluctuations were averaged and converted into C_n^2 which is the common measure of optical turbulence. The input to the scintillometer was the laser beam intensity and the output was a direct current voltage corresponding to a certain degree of turbulence strength. A typical current versus power density spectrum is shown in Figure 12 and the equipment aboard NKC-135/123 is shown in Figure 13.

An interferometer was also aboard NKC-135/123 but data obtained from it were not analyzed to obtain values of C_n^2. However, this device and measurement would be useful in future experiments. The interferometer used was a fast scanning shearing interferometer designed to obtain an optical interference parameter, the Modulation Transfer Function (MTF). MTF is a measure of the reduction in contrast that occurs from the object to the image over the spectrum of frequencies. In this experiment the MTF was obtained every $8X10^{-3}$ seconds and averaged every 30 seconds. Such measurements of MTF are: (1) dependent on the strength of the turbulence, (2) dependent on the scale of the turbulence, and (3) characterized by means and probabilities as a function of spatial frequency.

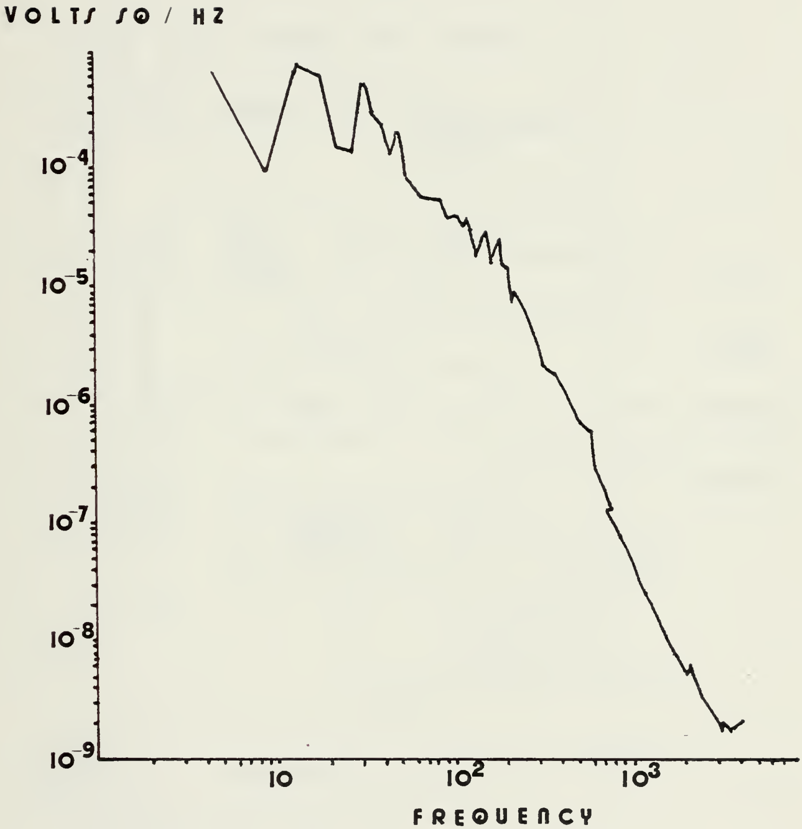


Figure 12. Typical Current vs. Frequency Scintillometer Graph.

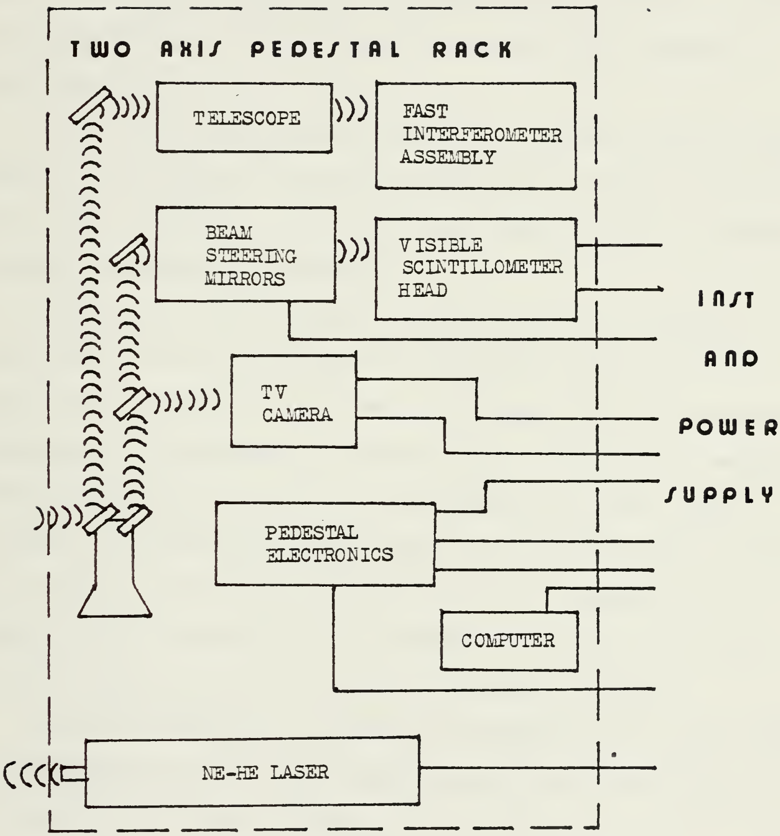


Figure 13. Instrumentation Aboard NKC-135/123.

MTF values may be converted to C_n^2 values. To obtain C_n^2 each MTF result would be resolved into Fourier components. The spectral contrast curves due to the diffraction limitations of the equipment would be removed and atmospheric C_n^2 values determined from the remaining curves. Such techniques were unavailable, but interferometer MTF data can still be interpreted qualitatively for conclusions about this experiment. See Figure 14.

Other sensors aboard NC-135/371 included a special outside air temperature device capable of measuring temperatures to within one hundredth of a degree centigrade. Both aircraft were equipped with the standard airspeed indicators and altimeters.

A major part of the experiment, but not one directly involved in obtaining C_n^2 values, was the Navy S-2 Atmospheric Sampler aircraft. This aircraft provided air temperature measurements, dewpoint temperature measurements and measurements of aerosol size and density. For aerosol size and density an aerosol particle spectrometer was used. Seven channels of this spectrometer were used, two for particle radii of .35 to .6 microns, two for particle radii of 1.05 to 1.8 microns. All samples taken by this aircraft were eventually converted to particles per cubic centimeter and presented as such (Figures 15 and 16).

Whereas the experimental procedure and equipment have been described in the preceding section, associated weather phenomena and results will be described in the next sections.

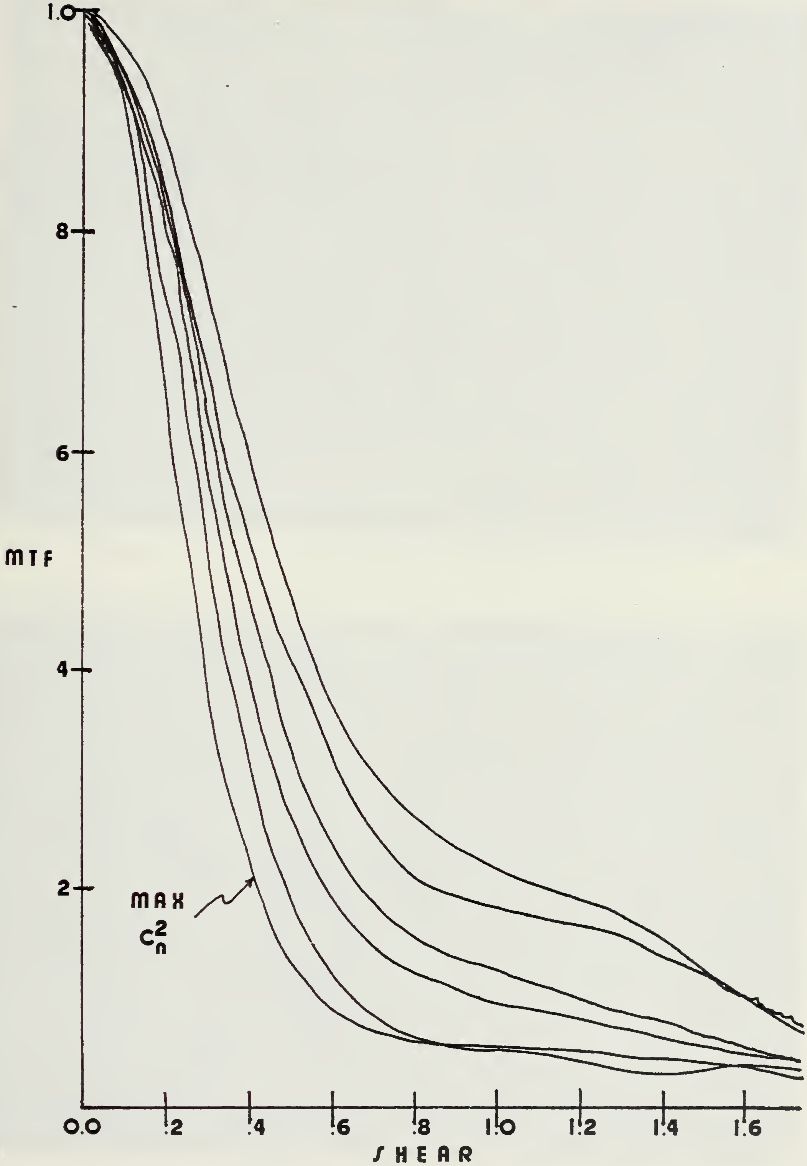


Figure 14. MTF Curve.

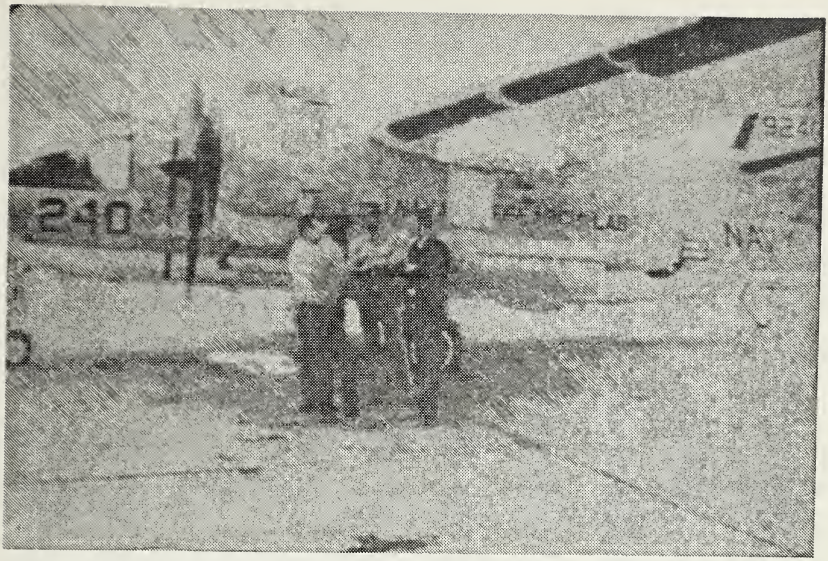


Figure 15. Navy S-2 Atmospheric Sampler on Ground.

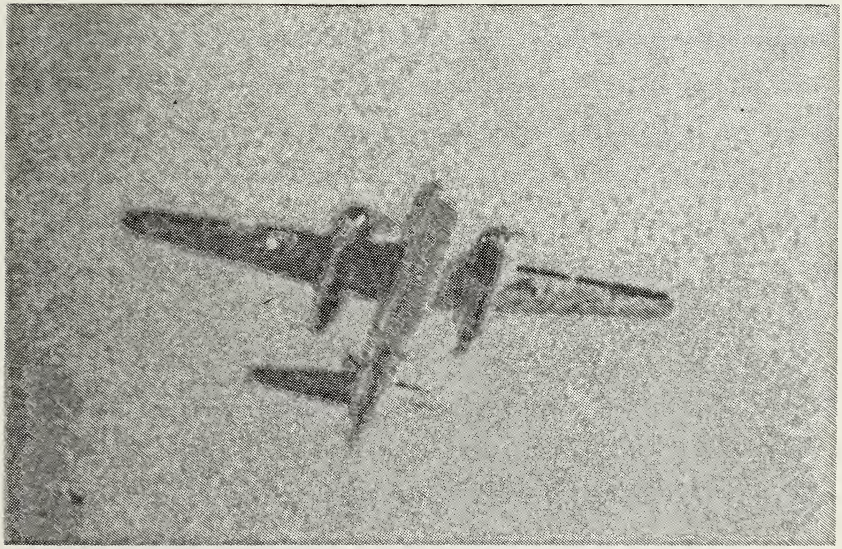


Figure 16. Navy S-2 in Flight over Acania.

V. THE SYNOPTIC WEATHER PATTERN

Synoptic weather conditions played an important role in the experiment. Delays and changes occurred which added significantly to the experiment. Weather for the central California coast during late summer is generally cool and foggy. Cold offshore water and the warm air associated with the eastern Pacific High combine to form fog and low stratus off the coast. A summer heat low normally leads to onshore flow and hence, the fog and stratus over the coast. September is a transition month between the relatively foggy summer and the relatively clear fall and there are alternating periods of fog and clear weather. September 1975 was no exception to this general pattern.

The execution of the experiment was delayed due to persistent fog and stratus in the designated flying area. A stationary high pressure system and the associated strong marine inversion maintained the fog and stratus. The C-135 aircraft arrived from Kirtland AFB, New Mexico on 10 Sep and were scheduled to fly on 11 and 12 Sep. The aircraft had to maintain visual flight rules (VFR) because of the close proximity of the two aircraft. They could not maintain VFR under fog and stratus conditions. The R/V Acania sailed from Monterey at 0030PDT on 11 Sep to be on station if weather conditions were acceptable. On the 11th and 12th, personnel aboard the Acania performed preliminary testing of the Kytoon, Airfoils, shipboard instrumentation and the thermosonde. The S-2 aircraft flew overhead on the 11th and 12th but on 12 Sep the Acania returned to Monterey to await better weather conditions.

On 14 Sep an upper level low began to develop off the California coast. With this synoptic change the Acania left Monterey early on 15 Sep and the aircraft and crews were alerted. On 15 Sep the upper level low was reflected at the surface by a weak low pressure circulation near 130°W and 34°N which was east southeast of the experiment area. This combined upper level low and weak surface circulation caused large scale subsidence ahead of this system. The subsidence was responsible for dissipating the low marine inversion and the fog and stratus in the area of the experiment.

On 15 Sep the area of the experiment was relatively clear and with excellent flying conditions. A jet stream maximum in the western side of the trough led to the trough intensifying and yielded further subsidence in the area of the experiment. Only scattered clouds existed in the vicinity of the Acania. Figure 17 shows the 500 mb flow on 15 Sep and Figure 18 the SMS satellite picture of 15 Sep. Figure 19 shows the temperature sounding taken by the S-2 aircraft in the area of the experiment. The S-2 Atmospheric Sampler observed a high inversion with a base at approximately 3200 feet and a top at approximately 4000 feet.

On 16 Sep the area was again relatively clear with good flying conditions. The jet stream maximum had rotated around the trough and the system weakened. The weakening allowed the marine inversion to become reestablished. The S-2 measured a marine inversion with a base at approximately 1300 feet and a top at 2300 feet. See Figure 20 for the 500 mb flow on 16 Sep, Figure 21 for the Synchronous Meteorological Satellite (SMS) picture of 16 Sep, and Figure 22 for the S-2 sounding of the experiment.

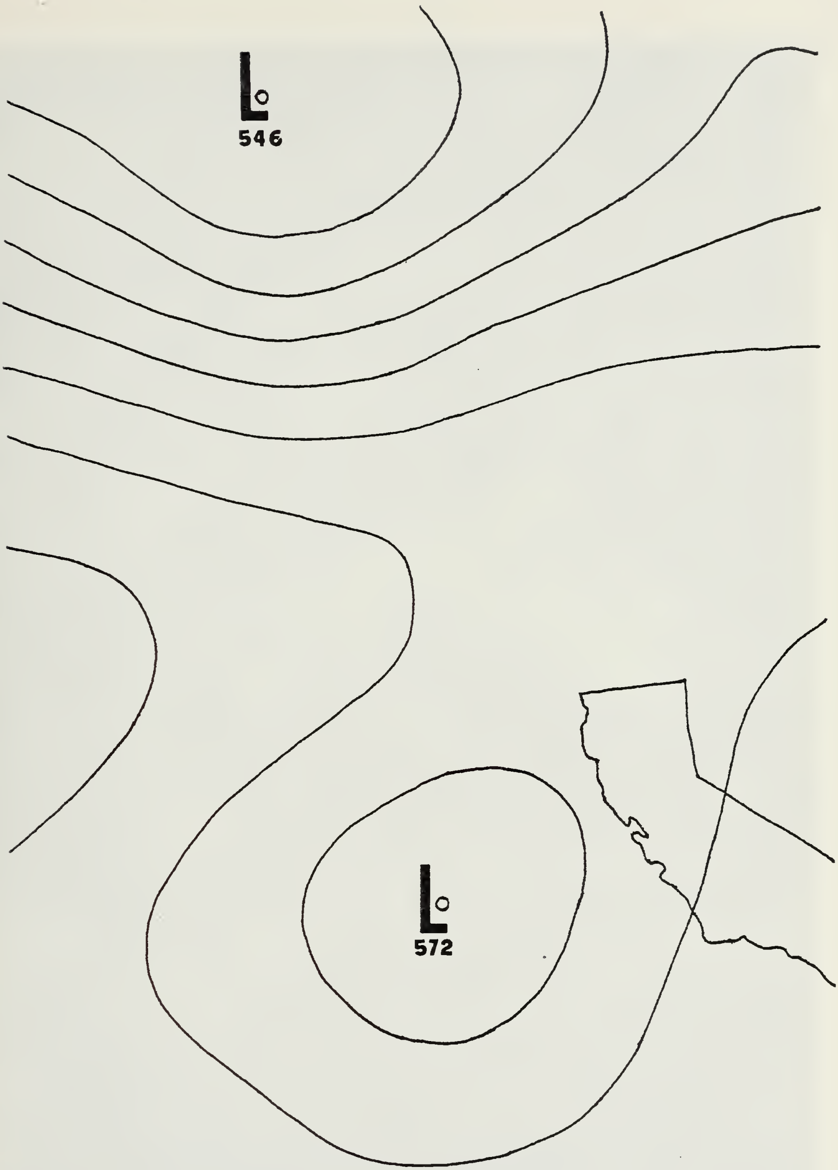


Figure 17. 500 mb Chart, 12Z 15 Sep 75.

Figure 18. SMS-2 Satellite Photograph of 2115Z 15 Sep 75.

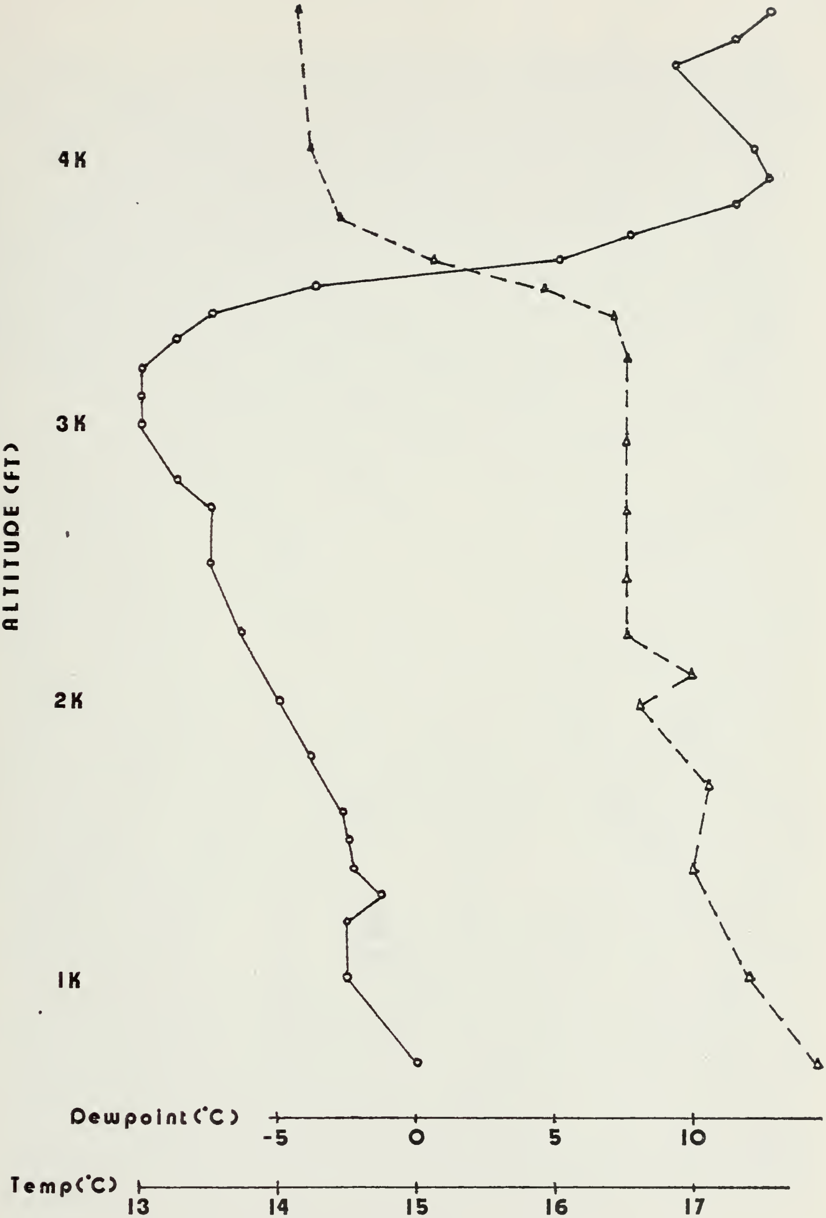


Figure 19. S-2 Temperature Sounding of 15 Sep 75.

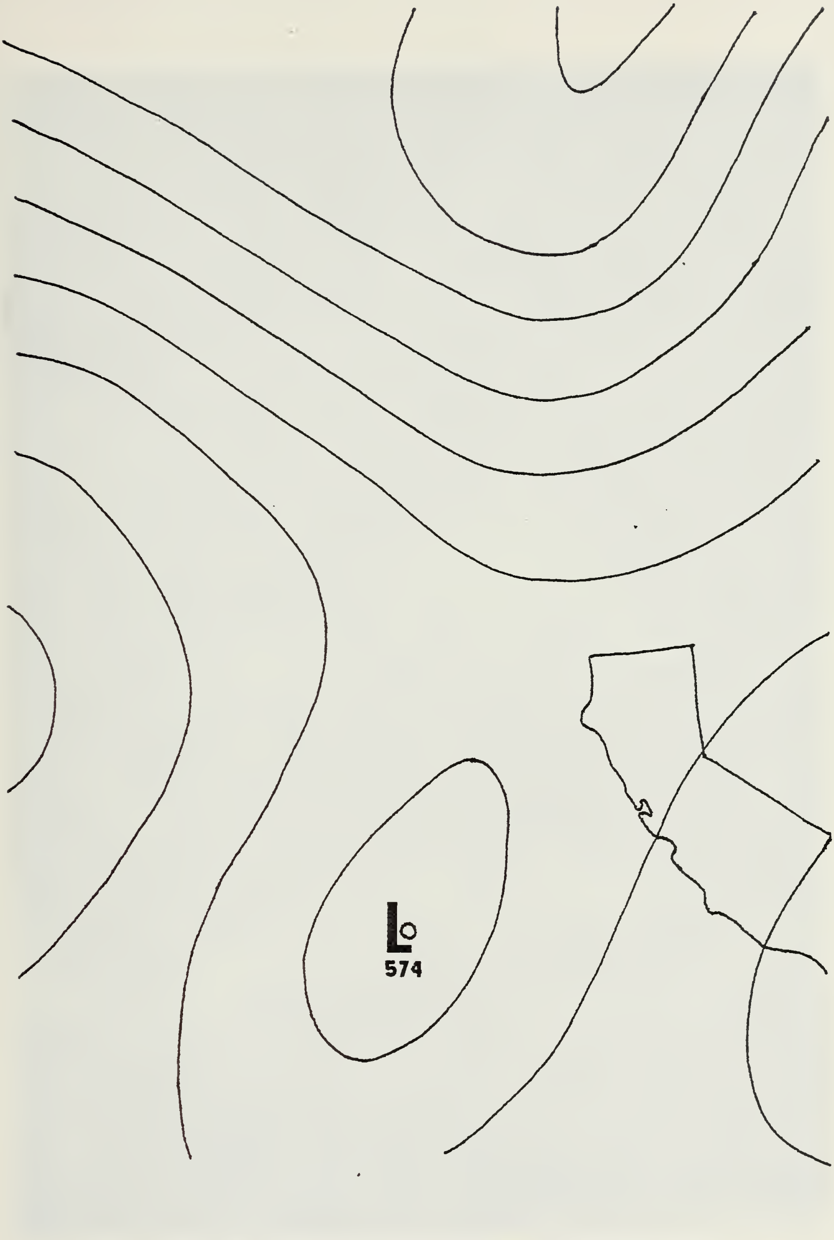


Figure 20. 500 mb Chart of 12Z 16 Sep 75.

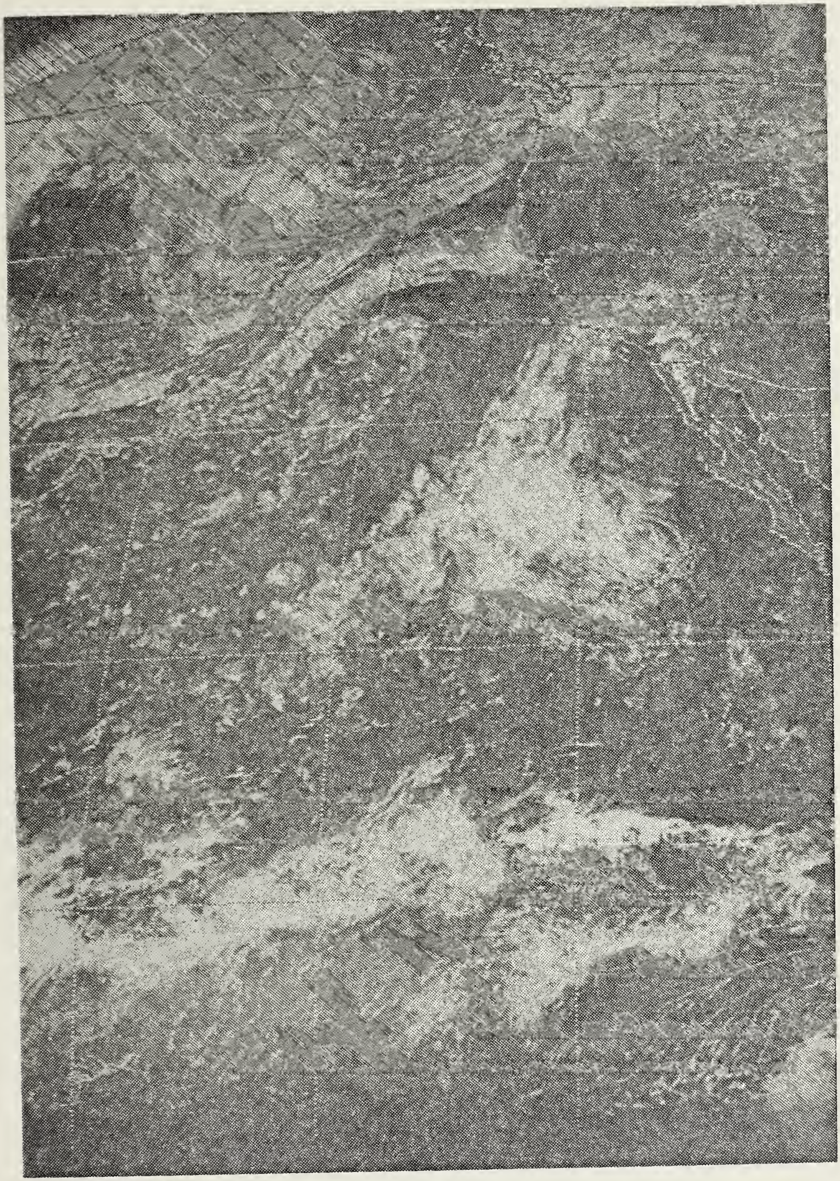


Figure 21. SMS-2 Satellite Photograph of 2145Z 16 Sep 75.

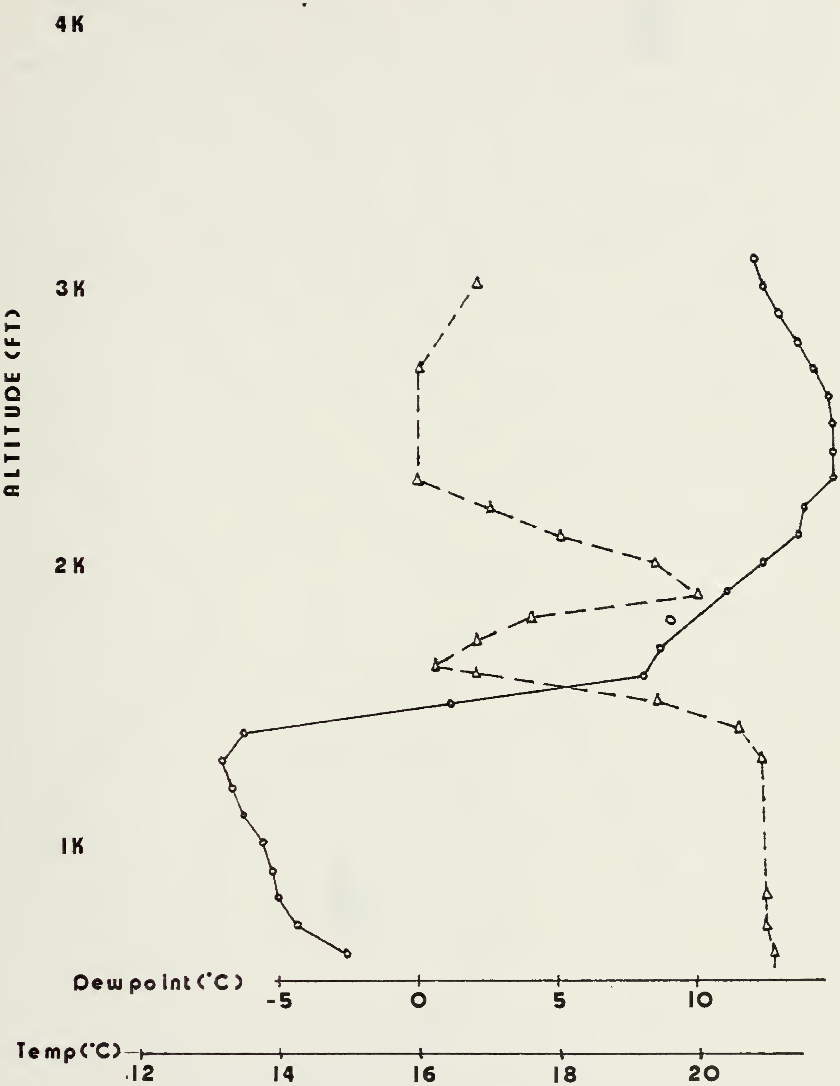


Figure 22. S-2 Temperature Sounding of 16 Sep 75.

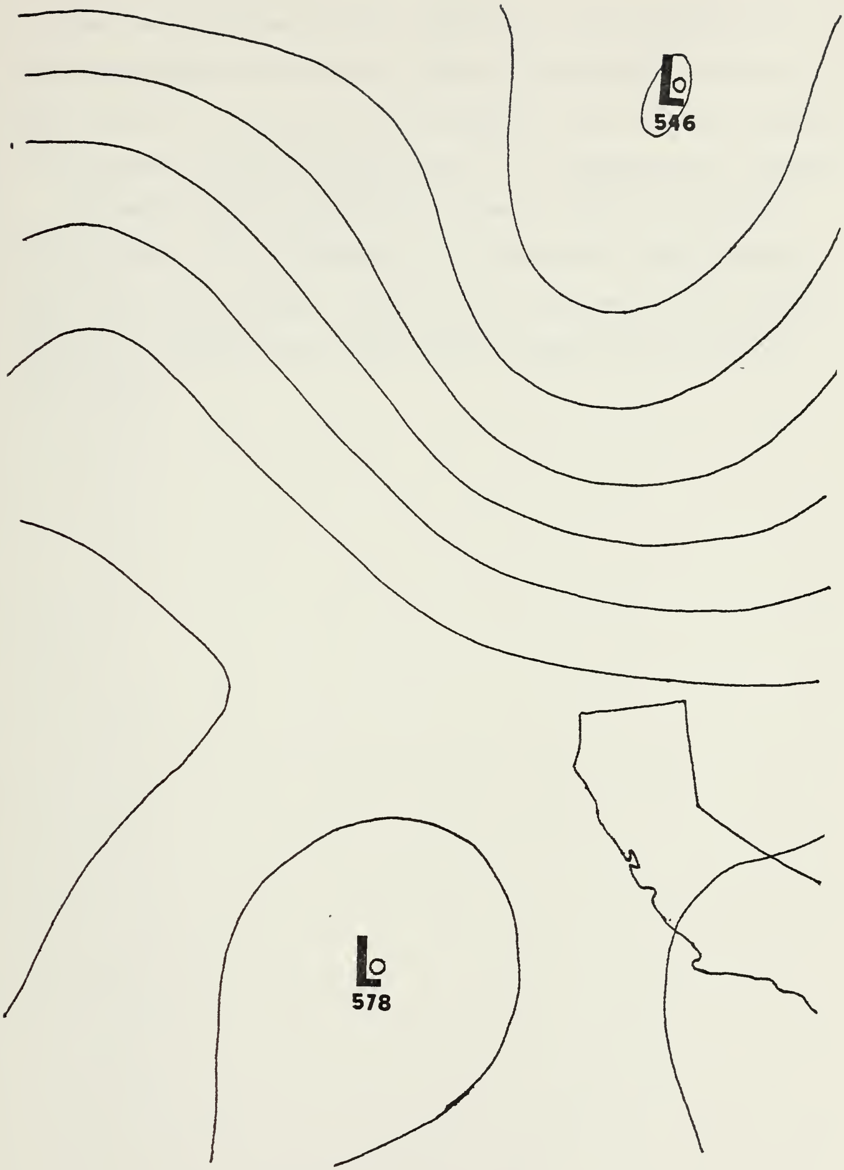


Figure 23. 500 mb Chart of 00Z 17 Sep 75.

Near the end of the 16th after completion of the experiment the jet stream became reestablished to the north over Washington State. With this shift the upper level low continued to fill and high pressure at the surface continued the development of an intense marine inversion.

The weather pattern provided two different types of environments for C_n^2 values. One environment was a cloudless well mixed boundary layer with a high inversion and the second environment was more typical of coastal California with a stable marine boundary layer and with a low inversion.

VI. RESULTS

Results from the various analyses will be discussed separately in this section. First, atmospheric sounding data were analyzed for California coastal stations for comparisons with the overwater sounding taken by the S-2 aircraft. Second, shipborne data were analyzed to determine its compatibility with the kiteborne thermosonde data taken from the ship. Third, thermosonde data were analyzed to compare with current theory, with the shipborne data, and with the scintillation data from the C-135s. Fourth, scintillometer data were compared with that from the thermosonde. Lastly, interferometer data were examined for compatibility with both the scintillometer data and the thermosonde data.

A. SOUNDINGS

Analyses of atmospheric soundings were made to determine if overland coastal soundings were adequate to describe overwater soundings. Available California coastal soundings were examined for the time period of the experiment and compared to the S-2 soundings taken overwater. The important features of all the soundings were the vertical extent and heights of the inversions. Table I shows the bases and the tops of the inversions evident in each of the soundings. The inversion heights and the features overwater were not evident in the soundings taken overland. On 15 Sep the S-2 recorded an inversion base in the area of the experiment of 3200 ft whereas all the coastal stations were reporting bases from 1300 to 1600 ft. The inversion tops

TABLE I.

INVERSION BASES AND TOPS, 15 AND 16 SEP 75

LOCATION	TIME (Z)	BASES		TOPS		CLOUDS
			15 SEP 75			
SAN DIEGO	1200	1400FT	.4KM	3600FT	1.11KM	900FT
OAKLAND	1200	1400	.4	2800	.83	1300
PT MUGU	1200	1400	.4	4750	1.45	300
MONTEREY	1655	1600	.5	2500	.75	
PT MUGU	1800	1400	.4	2300	.65	1000
S-2 AIRCRAFT	2040	3200	.95	3700	1.12	CLEAR
MONTEREY	2045	1300	.38	3000	.92	
			16 SEP 75			
SAN DIEGO	0000	800FT	.23KM	1800FT	.55KM	11000FT
		12600	3.8	13600	4.12	
PT MUGU	0000	1000	.3	1750	.52	9500
OAKLAND	0000	1500	.48	3000	.91	
SAN DIEGO	1200	SFC	SFC	1200	.38	12000
		15400	4.7	16000	4.88	
PT MUGU	1200	SFC	SFC	2100	.61	9000
		14500	4.4	16000	4.88	
OAKLAND	1200	1700	.55	2700	.82	FOG
MONTEREY	1758	SFC	SFC	400	.11	700
		1000	.3	2600	.75	
S-2 AIRCRAFT	2105	.350	.4	2800	.85	1200
MONTEREY	2200	1350	.4	2150	.62	900

on 15 Sep showed that the soundings which were closest in location to the experiment; Oakland, Monterey, and Point Mugu; had much lower inversion tops than did the S-2. Those stations which reported top heights near what the S-2 recorded were much further away. On the 16th all sounding locations had low level inversions and Oakland, Monterey, and Pt Mugu most closely approximate what the S-2 recorded. The coastal soundings on the 16th were adequate to describe overwater soundings but only having a one day sample was not enough to draw any conclusions.

B. SHIPBOARD C_n^2 DATA

The analysis of shipborne data was a comparison of C_n^2 values derived from C_T^2 measurements on the bow of the Acania and also C_T^2 measurements from the thermosonde above the ship. C_T^2 values were converted to C_n^2 using equation (1). Comparisons were made with Wyngaard et al (1971) prediction that in an unstable surface layer C_n^2 should decrease proportionately to $z^{-4/3}$. Stability was determined from the Richardson Number which was computed as:

$$Ri = \frac{g(d\overline{\theta}/dz)}{T(dU/dz)^2} \qquad (4)$$

Richardson Numbers for the 15th and 16th of September appear in Table II. A Richardson Number of less than -1 is sufficiently unstable for the $z^{-4/3}$ relationship to apply. Table II shows that the surface layer met these criteria since Richardson Numbers less than -1 occur from 2221Z to 2309Z. The values of C_n^2 from the thermosonde (see Figure 26) indicate a constant value with height during this time period so the $z^{-4/3}$ relationship does not hold in this case.

TABLE II

RICHARDSON NUMBERS, 15 AND 16 SEP 75

15 SEP 75		16 SEP 75	
TIME(Z)	RICHARDSON NO.	TIME(Z)	RICHARDSON NO.
2002	-0.71	1746	-0.25
2005	-0.67	1759	-0.87
2028	-0.58	1811	-0.65
2040	-0.63	1822	-0.35
2055	-0.40	1834	-0.21
2109	-0.36	1847	-0.11
2120	-0.33	1858	-0.04
2131	-0.34	1909	-0.09
2142	-0.32	1921	0.02
2221	-2.26	1933	-0.13
2234	-6.88	1945	-0.49
2246	-1.38	1956	-0.41
2258	-1.93	2010	-0.29
2309	-1.03	2021	-1.77
2319	1.31	2035	-0.46
2330	1.02	2049	-0.61
2346	-0.91	2056	-0.71
2357	-1.15	2107	-0.73
0007	-1.95	2119	-0.61
		2133	-0.39
		2146	-0.47
		2157	-0.33
		2209	-0.51
		2219	-0.52
		2235	-0.36
		2247	-0.31
		2259	-0.50

Shipboard data were examined with respect to its diurnal variation. On 15 Sep only one level was working, level 3 at 7.6 meters and is shown in Figure 24. A slight increase in C_n^2 occurred through the afternoon. This is the expected trend since C_n^2 should increase as the near surface potential temperature gradient increases.

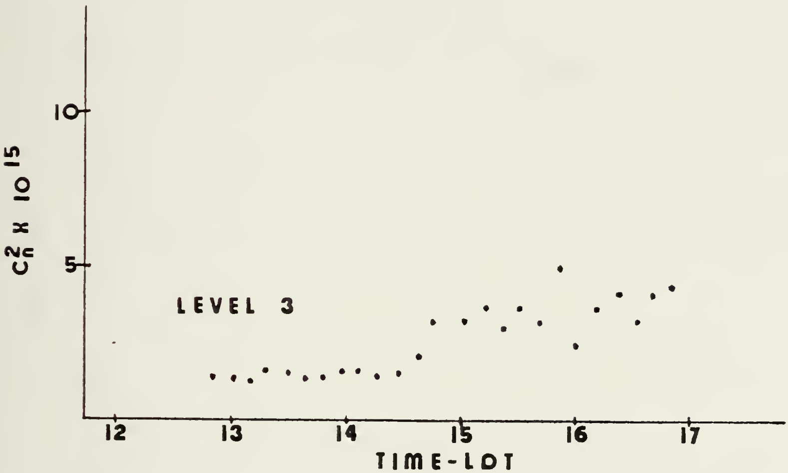


Figure 24. Diurnal Change of C_n^2 for 15 Sep 75.

On 16 Sep both levels, at 4.2 and 7.6 meters, were working and showed a definite convergence of C_n^2 into the afternoon as shown in Figure 25.

C. KITEBORNE C_n^2 DATA

The analysis of the thermosonde data was undertaken to see if C_n^2 was a maximum within the inversion as suggested by Lawrence and Ochs (1972), if it compared favorably with the scintillometer data and also, if the scaling of the data was approximately $z^{-4/3}$ as suggested by Frisch and Ochs (1974). There was one thermosonde run on 15 Sep

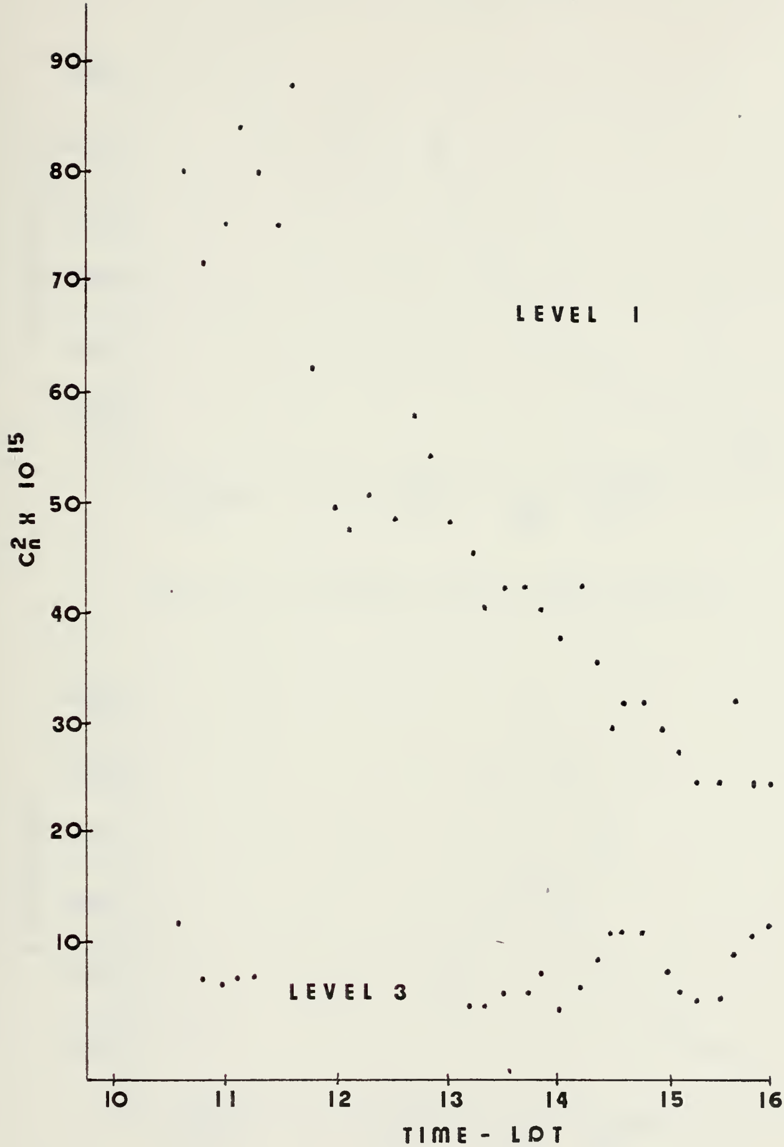


Figure 25. Diurnal Change of C_n^2 for 16 Sep 75.

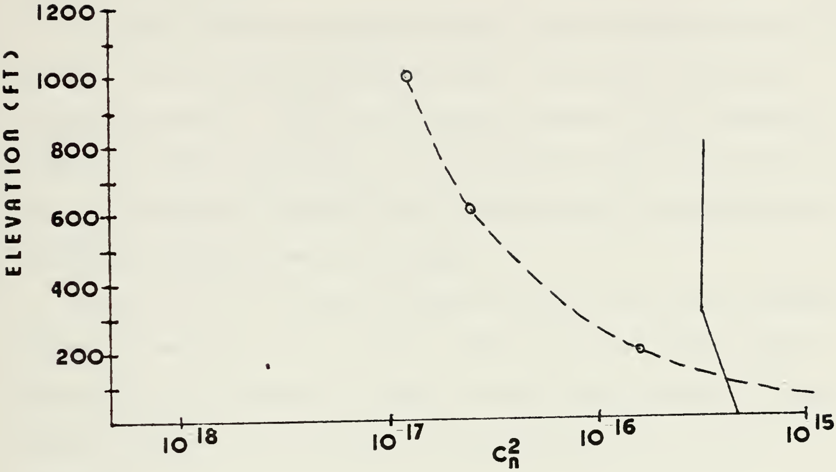


Figure 26. C_n^2 Sounding 1952Z to 2140Z, 15 Sep 75.

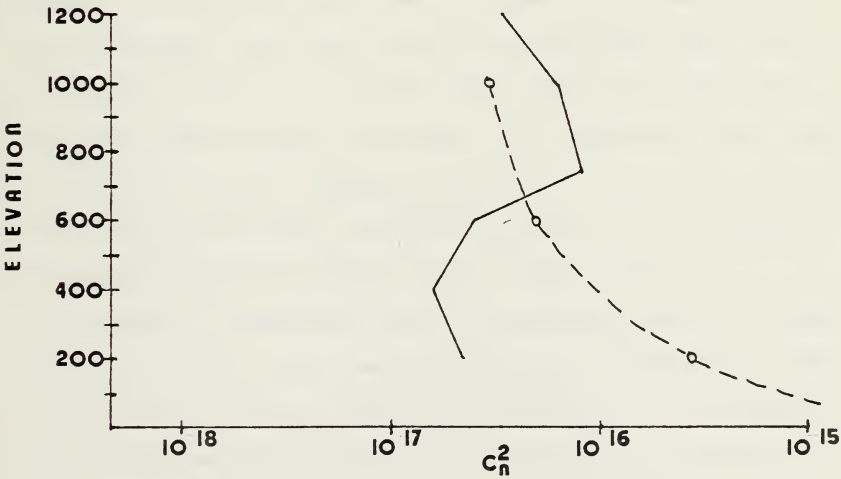


Figure 27. C_n^2 Sounding 1840Z to 1925Z, 16 Sep 75.

suspended by the Kytoon and three runs were completed on 16 Sep suspended by the Jalbert Airfoil.

C_n^2 values obtained on these four runs appear in Figures 26, 27, 28, and 29. The data obtained from individual runs clearly reflect the synoptic situation. On 15 Sep the nearly constant C_n^2 was indicative of a well mixed surface layer. On the 16th the large variations of C_n^2 are an indication of layering in the atmosphere and to be expected with a strongly developing marine inversion.

Values of C_n^2 at different heights from each of the three platforms appear in Tables III, IV, V, and VI. None of the thermosonde passes went through the inversions, neither the upper level inversion nor the marine inversion, so an inversion related maximum in C_n^2 was not measured.

A comparison of C_n^2 data from the thermosonde with that from the aircraft's scintillometer showed that several orders of magnitude existed between the C_n^2 data computed from C_T^2 values and that measured by optical methods. This occurs even when the equivalent Pearson value is used (Pearson, 1975). The data that were compared were those which were taken during the same time period. One reservation on these interpretations is that the thermosonde had been used many times in the dry southwestern United States environment but never in the moist marine environment where salt deposits could have been a factor.

Although the thermosonde results in the figures reflect the synoptic situation the data do not agree with theoretical relationships. Tsvang (1969) and Frisch and Ochs (1975) have observed the $z^{-4/3}$ distribution of C_T^2 under unstable conditions. C_T^2 is directly proportional to C_n^2 and, hence, C_n^2 should also be represented by a $z^{-4/3}$ relationship.

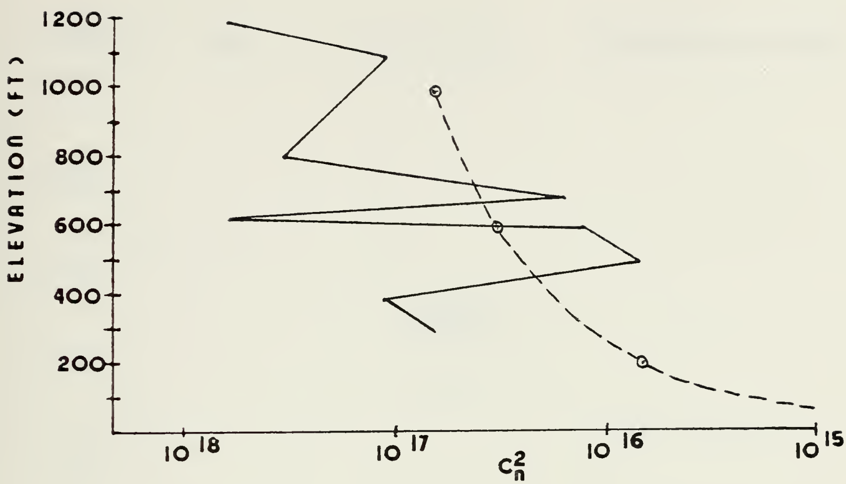


Figure 28. C_n^2 Sounding 1929Z to 2123Z, 16 Sep 75.

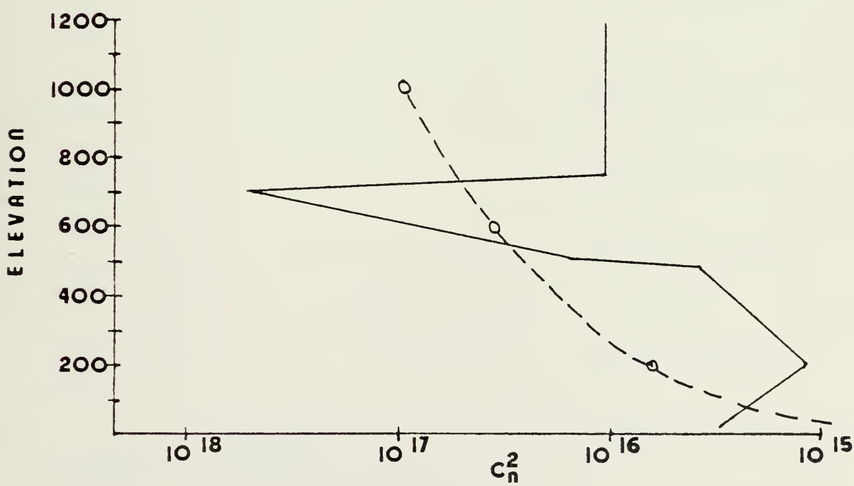


Figure 29. C_n^2 Sounding 2130Z to 2300Z, 16 Sep 75.

TABLE III. C_n^2 Values from All Platforms 1952Z-2140Z, 15 Sep 75.

ELEVATION	SHIP	SCINTILLOMETER	THERMOSONDE (EQUIVALENT)
1200			
1000			
900			
		5.96×10^{-14}	
		2.93×10^{-14}	
		1.24×10^{-14}	
800			
		2.92×10^{-16}	
			6×10^{-16} (1.5×10^{-15})
700			
			6×10^{-16} (1.5×10^{-15})
600			
			6×10^{-16} (1.5×10^{-15})
500			
			6×10^{-16} (1.5×10^{-15})
400			
			6×10^{-16} (1.5×10^{-15})
300			
			6×10^{-16} (1.5×10^{-15})
200			
			6×10^{-16} (1.63×10^{-15})
100			
			7×10^{-16} (1.7×10^{-15})
	6.3×10^{-14}		
	2.73×10^{-14}		
SEA LEVEL			

TABLE IV. C_n^2 Values from All Platforms 1840Z-1925Z, 16 Sep 75.

ELEVATION	SHIP	SCINTILLOMETER	THERMOSONDE (EQUIVALENT)
1200			5×10^{-17} (1.86×10^{-16})
1000			8×10^{-17} (2.68×10^{-16})
900			
800			
700			9×10^{-17} (2.94×10^{-16})
600			3.5×10^{-17} (1.43×10^{-16})
500			
400			2×10^{-17} (9.77×10^{-17})
300			2.5×10^{-17} (1.13×10^{-16})
200			3×10^{-17} (1.29×10^{-16})
100			
SEA LEVEL	6.03×10^{-14}		

TABLE V. C_n^2 Values from All Platforms 1929Z-2123Z, 16 Sep 75.

ELEVATION	SHIP	SCINTILLOMETER	THERMOSONDE (EQUIVALENT)
1200			2×10^{-18} (2.97×10^{-17})
1000			8×10^{-18} (5.6×10^{-17})
900			
			4×10^{-18} (3.97×10^{-17})
800			
		9.53×10^{-16}	
700			9×10^{-17} (2.9×10^{-16})
			3×10^{-18} (3.49×10^{-17}) 1×10^{-16} (3.2×10^{-16})
600			
		1.1×10^{-15}	
			2×10^{-16} (5.7×10^{-16})
500			
			1×10^{-17} (6.38×10^{-17})
400			
		1.02×10^{-15}	
			2×10^{-17} (9.77×10^{-17})
300			
		1.07×10^{-15}	
200			
100			
SEA LEVEL	5.61×10^{-15} $4,26 \times 10^{-14}$		

TABLE VI. C_n^2 Values from All Platforms 2130Z-2300Z, 16 Sep 75.

ELEVATION	SHIP	SCINTILLOMETER	THERMOSONDE (EQUIVALENT)
1200			1×10^{-16} (3.2×10^{-16})
1000			1×10^{-16} (3.2×10^{-16})
900			
800			1×10^{-16} (3.2×10^{-16})
700			3×10^{-18} (3.49×10^{-17})
600			
500			4×10^{-16} (1.05×10^{-15})
400			
300			
200			9×10^{-16} (2.2×10^{-15})
100			5×10^{-16} (1.26×10^{-15})
SEA LEVEL	9.13×10^{-15} 2.74×10^{-14}		

In Figures 26, 27, 28, and 29 is a $z^{-4/3}$ dashed line drawn to represent the theoretical distribution. This curve was constructed using the 4.2 meter C_n^2 value obtained from shipborne measurements as a starting point. These lines do not coincide with the non-smooth soundings. However, they could be viewed to be reasonable average values for the 1840Z-1923Z and 1929Z-2123Z soundings.

D. SCINTILLOMETER

Analyses of the scintillometer data were undertaken to see if C_n^2 values were a maximum in the inversion and how the data compared with the thermosonde data. C_n^2 values for times when the aircraft passed through the inversions are shown in Table VII. In seven out of nine cases there were order of magnitude increases in the C_n^2 values in the traverse through the inversion. This fact is not definitive, however, because there were frequent and apparently random order of magnitude changes throughout the traverse and, hence, values of C_n^2 were higher than had been expected. As Morris had suspected in 1972, the larger values of C_n^2 probably reflected boundary layer turbulence next to the skin of aircraft. In addition to the problems of aircraft boundary layer turbulence, this flight was the first of the rejuvenated ALL experiments and there were associated technical problems. A primary problem was the jitter or physical movement of the tracking benches. The jitter was caused by a combination of vibration and tracking error problems. The jitter fluctuations were readily seen on the strip chart records of the data which revealed large amplitude fluctuations of voltage not conducive with the normal scintillometer readout. Due to the jitter problems, only a few minutes of good data were available out of the nine passes taken each day. On 15 Sep only 45 minutes of

TABLE VII. Aircraft Measurement C_n^2 Values Through the Inversion.

15 Sep 75

INVERSION BASE: 3200FT INVERSION TOP: 3700FT

TIME(Z)	ALTITUDE(FT)	C_n^2
2041-20	2668	5.16×10^{-16}
2042-34	3626	3.82×10^{-16}
2044-43	4473	4.71×10^{-16}
2056-40	4107	4.08×10^{-14}
2057-25	3611	5.06×10^{-15}
2058-18	3142	2.29×10^{-15}
2108-25	2928	3.88×10^{-16}
2110-30	3461	4.37×10^{-15}
2111-20	3897	4.48×10^{-15}
2333-41	3901	1.69×10^{-15}
2334-44	3271	6.65×10^{-16}
2335-15	3065	1.22×10^{-15}
2343-45	3248	5.47×10^{-16}
2344-23	3633	1.25×10^{-15}
2344-58	3899	6.05×10^{-16}

16 Sep 75

INVERSION BASE: 1350FT INVERSION TOP: 2800FT

TIME(Z)	ALTITUDE(FT)	C_n^2
2042-50	2335	1.04×10^{-15}
2043-51	1890	7.98×10^{-16}
2044-40	1433	5.3×10^{-16}
2049-02	1470	5.73×10^{-16}
2050-08	2050	6.97×10^{-16}
2051-02	2465	1.13×10^{-15}
2052-09	2860	4.05×10^{-16}
2102-50	3091	7.77×10^{-16}
2104-03	2544	4.87×10^{-16}
2105-07	2193	3.0×10^{-16}
2106-06	1716	4.73×10^{-16}
2108-27	540	1.1×10^{-15}
2111-55	1141	1.04×10^{-15}
2113-10	1770	8.09×10^{-16}
2114-15	2301	9.16×10^{-16}
2115-25	2724	6.86×10^{-16}

usable data were obtained out of two hours and 20 minutes on station. On 16 Sep 27 minutes of usable data were obtained out of two hours and 17 minutes.

An example of the data obtained by the scintillometer is shown in Figure 12. C_n^2 is derived from the slope of the power curve over the frequency range.

E. INTERFEROMETER

The interferometer data were analyzed to determine if there was a definite correlation between optical measurement of C_n^2 and temperature measurement of C_n^2. C_n^2 values were not obtained from the interferometric measurements. The interferometer portion of the experiment was designed to obtain MTF values to determine the optical properties of the atmospheric medium between two airplanes. A fast shearing interferometer was used and MTF curves were taken every 8×10^{-3} seconds and averaged every 30 seconds. A simple qualitative relationship does exist and with the knowledge that C_n^2 should be a maximum within the inversion, the MTF with the maximum slope has the highest C_n^2 and therefore is most likely to be within the inversion. See Figure 14. The MTF values and the standard deviations of those values were provided by the Lincoln Laboratories ALL organization at the AFWL in New Mexico. Examination of these values led to the conclusion that upon the aircraft passing through the inversion the maximum MTF slope should occur if the standard deviation curve was appropriately steady. Table VIII shows these results. Most of the maximum MTF slopes occurred in the inversion if the standard deviation curves were taken into account. From this qualitative examination it is apparent that there is a correlation between optical and temperature measurement of C_n^2.

TABLE VIII. Modulation Transfer Function Values

ALTITUDE (KM)	MAX SLOPES	NO. OF MEAN MTFS	STAN DEV
1.22	1		GOOD
1.07	3	9	GOOD
.98	2		GOOD
.94	3		GOOD
1.07	2	14	GOOD
1.19	8		FAIR
1.1	1		GOOD
1.02	4	13	GOOD
.96	3		GOOD
.93	8		FAIR
1.06	12	13	POOR
1.19	13		POOR
1.16	2		GOOD
1.06	3	11	GOOD
.95	1		GOOD
.96	7		FAIR
1.06	9	14	FAIR
1.14	8		FAIR
1.0	14		POOR
.97	2	14	FAIR
.93	5		FAIR
.92	9		FAIR
.97	3	16	GOOD
1.04	1		GOOD
1.19	8		POOR
1.12	1	16	GOOD
1.01	11		POOR
1.11	9		FAIR
1.19	6	16	FAIR
1.24	7		FAIR
1.09	1		GOOD
1.2	2	15	GOOD
1.31	8		GOOD
1.32	2		GOOD
1.22	7	12	FAIR
1.11	12		POOR

TABLE VIII. Modulation Transfer Function Values (continued)

ALTITUDE (KM)	MAX SLOPES	NO. OF MEAN MTFS	STAN DEV
1.08	3		GOOD
1.18	14	15	POOR
1.29	15		POOR
.93	1		GOOD
.69	5	12	POOR
.54	8		POOR
.78	1		GOOD
.81	3	12	FAIR
.83	7		FAIR
.66	7		GOOD
.58	1	8	GOOD
.47	2		GOOD
.65	1		GOOD
.71	3	16	GOOD
.76	16		POOR
.76	3		FAIR
.75	1	17	POOR
.71	6		GOOD
.76	8		FAIR
.78	7	16	FAIR
.83	3		GOOD
.81	1		GOOD
.74	4	14	GOOD
.69	9		FAIR
.40	3		FAIR
.49	1	12	GOOD
.63	2		POOR

VII. CONCLUSIONS

Several conclusions can be drawn from this experiment. With respect to comparisons of overwater and overland soundings, the sample was not large enough to state that overwater soundings could be implied by those overland. Shipborne data provided reasonable stability values based on the synoptic weather situation and provided reasonable initial values for C_T^2 height distributions. The shipborne data also indicated that differences between C_n^2 values at different levels tend to decrease in late afternoon hours. The thermosonde data reflected the synoptic weather situation with nearly constant values in the well mixed layers and large variations in the more stable layers. C_n^2 soundings on the 16th agreed with the $z^{-4/3}$ approximation for the average C_n^2 versus height. Aircraft scintillometer data, compared with other C_n^2 data, have very little correlation with the others. Equipment problems and therefore questionable readings decreased the validity of the scintillometer data. Comparisons of the inversion heights with aircraft penetrations of the inversion indicated that C_n^2 values reached maxima in the inversions. The interferometer measurements of MTF imply that a maximum C_n^2 would have been measured in the inversion by this optical method. This implies that temperature determined C_n^2 values are comparative to optically determined C_n^2 values through an inversion.

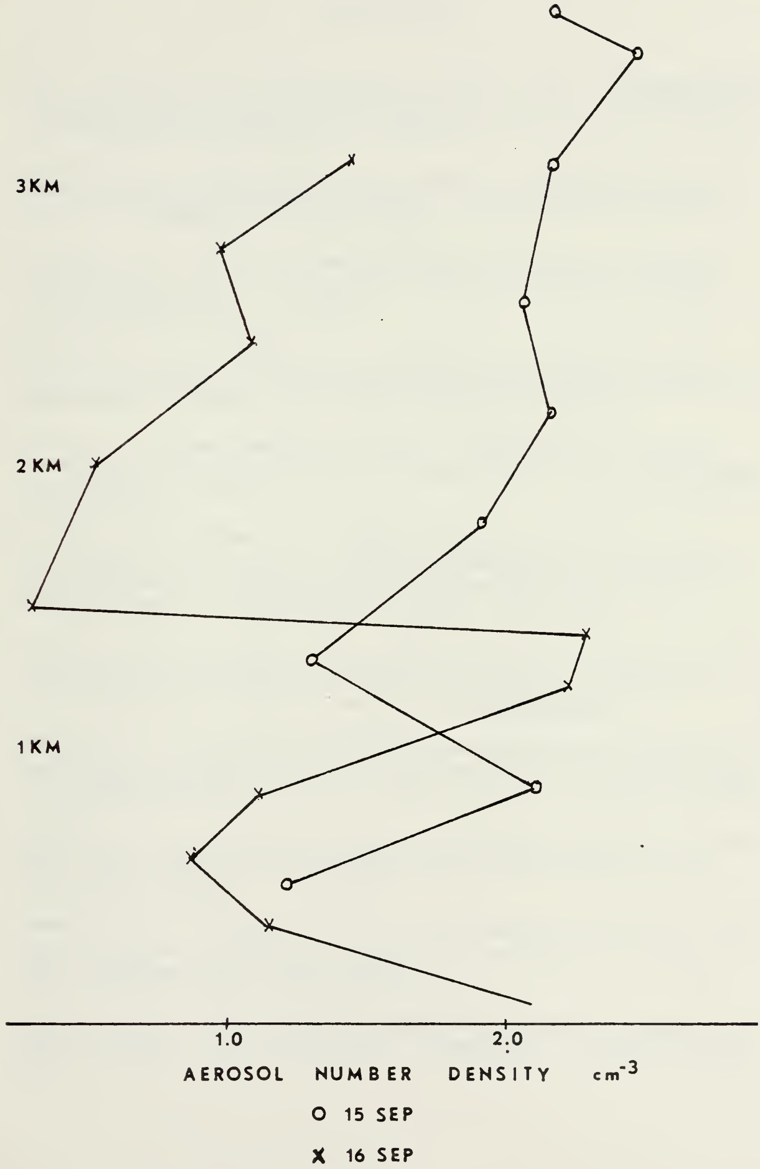
APPENDIX A

LASER CHARACTERISTICS

1.	MODEL	124A SPECTRA PHYSICS
	TYPE	He-Ne CONTINUOUS WAVE
	POWER	15MW
	OUTPUT DIAMETER	2.54CM
	FULL ANGLE DIVERGENCE	10MRAD
	WAVELENGTH	6328A
	SAFE EYE EXPOSURE DIST	17CM
2.	MODEL	RCA LD2174
	TYPE	He-Ne CONTINUOUS WAVE
	POWER	5MW
	OUTPUT DIAMETER	2MM
	FULL ANGLE DIVERGENCE	15MRAD
	WAVELENGTH	6328A
	SAFE EYE EXPOSURE DIST	0.91M

APPENDIX B

AEROSOL SOUNDINGS



BIBLIOGRAPHY

1. Air Force Special Weapons Center Test Plan, 1975: Advanced Radiation Program, Airborne Laser Laboratory Project Airborne Laser Propagation Experiments II. 25 Aug 75.

2. Businger, J. A, Wyngaard, J. C., Izumi, Y. and Bradley, E. F., 1975: "Flux-Profile Relationships in the Atmospheric Surface Layer," J. Atmos. Sci., 28, 181-189.

3. Curatola, C., 1975: "Thermosonde Data in Support of Marine Boundary Layer Investigation 15-16 Sep 75." Letter to Naval Postgraduate School. 14 Nov 75.

4. Davidson, K. L., Fairall, C., Houlihan, T., and Schacher, G., 1976: "Description of Optically Relevant Turbulence Parameters," Department of Meteorology, Naval Postgraduate School.

5. Friehe, C. A. and LaRue, J. C., 1973: "Dependence of Optical Refractive Index on Humidity and Temperature." 1973 Meeting OSA. Paper FF-18. P. 1327.

6. Friehe, C. A., LaRue, J. C. Champaigne, F. H., Gibson, C. H., and Dreyer, G. F., 1975: "Effects of Temperature and Humidity Fluctuations on the Optical Refractive Index in the Marine Boundary Layer." J. Opt. Soc. Am. 65/12. 1502-1511.

7. Frisch, A. S. and Ochs, G. R., 1975: "A Note on the Behavior of the Temperature Structure Function Parameter in a Convective Layer Capped by a Marine Inversion." J. Applied Met.

8. Hufnagel, R. E., 1966: "An Improved Model Turbulent Atmosphere." Restoration of Atmospherically Degraded Images, National Academy of Sciences. 2,14.

9. Koprov, V. M. and Tsvang, L. R., 1966: "Characteristics of very Small-Scale Turbulence in a Stratified Boundary Layer." Izv. Fiz. Atmos. Okean.2. 1142-1150.

10. Lawrence, R. S. and Ochs, G. R., 1972: "Temperature and C_n^2 Profiles Measured over Land and Ocean to 3 Km above the Surface." NOAA Technical Report ERL 251-WPL 22.

11. Morris, G. J., 1973: "Airborne Laser Beam Propagation Measurements of High Altitude Atmospheric Turbulence." J. Opt. Soc. Am. 63. 263-270.

12. Paulson, C. A., Leavitt, E., and Fleagle, R. G., 1972: "Air-Sea Transfer of Momentum, Heat and Water Determined from Profile Measurements during BOMEX." J. Phys. Oceanog. 2. 437-447.

13. Pearson, J. E., 1975: "Comparison of Scintillometer and Microthermometer Measurements of C_n^2." J. Opt. Soc. Am. 65/8. 938-941.

14. Tsvang, L. R., 1969: "Microstructure of Temperature Fields in the Free Atmosphere." Radio Science 4/12. p. 1175.

15. Volkov, Yu. A., Kukharets, V. P., and Tsvang, L. R., 1968: "Turbulence in the Boundary Layer of the Atmosphere above the Steppe and the Sea." Izv. Fiz. Atmos. Okean. 4. 1026-1041.

16. Wyngaard, J. C., Izumi, Y., and Collins, S. A., 1971: "Behavior of the Refractive Index Structure Parameter near the Ground." J. Opt. Soc. Am. 61. p. 1646.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 63Ha Department of Meteorology Naval Postgraduate School Monterey, California 93940	1
4.	Assoc. Professor K. L. Davidson, Code 63Ds Department of Meteorology Naval Postgraduate School Monterey, California 93940	9
5.	Assoc. Prof. T. M. Houlihan, Code 69 Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93940	1
6.	Assoc. Prof. W. W. Denner, Code 68 Department of Oceanography Naval Postgraduate School Monterey, California 93940	1
7.	Maj. G. Thompson AFWL/WE Kirtland AFB, New Mexico 87116	1
8.	Dr. E. Kelsall Box 18027 Sandia Base, New Mexico 87105	1
9.	Lt. M. M. Hughes PMS 405 Naval Sea Systems Command Washington, D. C. 20632	2
10.	Capt Richard H. Paine 386C Bergin Monterey, California 93940	1

11. Capt. Harry H. Hughes 1
AFIT/CIPF
Wright-Patterson AFB, Ohio 45433

12. Air Weather Service 1
AWVAS/TF
Scott AFB, Illinois 62225

Thesis 169767
P1193 Paine
c.1 A three platform experiment on optical turbulence in the marine boundary layer.